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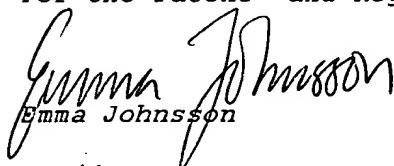
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Technical field

The present invention relates to a rate adaptive pacemaker comprising a means for determining the demand of the patient's organism, a pacing rate controlling means for controlling the pacing rate in response to the patient's demands and a pacing rate limiting means for preventing the pacing rate from becoming too high.

Background Art

Too high pacing rates can appear in a rate adaptive pacemaker due to the physical demand of the patient's organism and heart. This may cause lack of oxygen supply to the myocardium. Thus, in certain conditions the heart may not be able to satisfy the physiological needs of the patient's organism and heart if the pacing rate is not limited.

Several different proposals for limiting the pacing rate upwards have been presented. Thus in e.g. US-A-5,350,409 a rate adaptive pacemaker is described having an upper pacing limit programmed beyond which rate the pacemaker will not generate and deliver stimulation pulses. US-A-5,792,195 discloses an acceleration sensed safe upper rate envelope for calculating the haemodynamic upper rate limit for a rate adaptive pacemaker. From the output signal from an accelerometer the time of occurrence of a specific heart sound in relation to a previously occurring ventricular depolarization event is then derived and this heart sound information is used to establish a haemodynamic upper rate limit for the pacemaker. Also EP-0 879 618 A1 describes a rate modulated heart stimulator having a programmable maximum sensor rate. This heart stimulator also includes an ischemia detector and in response to the detection of an ischemia the maximum allowable stimulation rate is decreased.

The limit values are determined from patients' diagnosis and the setting can be either constant or externally programmable.

5 The purpose of the present invention is to propose a new way of continuously automatically limiting the pacing rate upwards according to the current ability of the patient's heart.

10 Disclosure of the Invention

This purpose is obtained by a rate adaptive pacemaker according to claim 1.

15 Thus, in the pacemaker according to the invention the myocardium energy consumption and energy supply can be kept in balance, and since this relation, and not the heart rate, is of primary importance, the patient can feel more healthy and comfortable in various everyday life conditions, also in conditions of active work.

20 Preferred embodiments are set forth in the dependent claims.

25 According to an advantageous embodiment of the pacemaker according to the invention the pacing rate limiting means is adapted to limit the pacing rate upwards such that the energy consumed by the myocardium always is less than the energy supplied to the myocardium. In this way lack of oxygen supply to the myocardium is avoided.

30 According to another advantageous embodiment of the pacemaker according to the invention said pacing rate limiting means includes an upper limit setting means for setting an upper limit value for the pacing rate, and an upper limit determining means to determine the relation between energy supplied  
35 to the myocardium and energy consumed by the myocardium for calculating an upper pacing rate limit value from said relat-

ion for supply to said upper limit setting means. Thus, in this way the actual pacing rate is continuously compared to a set upper limit value and the actual pacing rate is limited to a maximum value equal to this limit value.

5

According to still other advantageous embodiments of the pacemaker according to the invention said pacing rate limiting means is adapted to limit the pacing rate such that the inequality

$$(t_{\text{diast,rest}}/t_{\text{diast}}) \cdot (SV/SV_{\text{rest}}) < CR \quad (1)$$

is satisfied, alternatively said upper limit determining means is adapted to determine actual coronary resistance ratio (CRR) from the equation

$$\text{supplied energy} = \text{consumed energy} \quad (2)$$

and determine an upper pacing rate limit from the relation between actual coronary resistance ratio (CRR) and coronary reserve (CR), or said upper limit determining means is adapted to determine the upper pacing rate limit value from the equation

20

$$\text{upper pacing rate limit} = (60 \cdot CR) / [t_{\text{diast,rest}} \cdot (SV/SV_{\text{rest}}) + CR \cdot t_{\text{syst}}] \quad (3)$$

where  $t_{\text{diastrest}}$  denotes diastolic duration for the patient in rest conditions,  $t_{\text{diast}}$  actual diastolic duration for the patient, SV and  $SV_{\text{rest}}$  actual stroke volume and stroke volume for the patient in rest conditions respectively, and  $t_{\text{syst}}$  the actual systolic duration. A bioimpedance measurement unit is preferably provided to measure the intracardiac bioimpedance as a function of time and determine therefrom actual stroke volume SV and actual diastolic and systolic duration  $t_{\text{diast}}$  and  $t_{\text{syst}}$  respectively. Since the electrical bioimpedance can be effectively used to determine cardiac parameters, in particular the parameters mentioned above can be obtained

25

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from the time variation of the bioimpedance measured between the tip of an intracardiac electrode and the housing of a pacemaker when an excitation current proceeds from the electrode tip, the parameters needed for preventing the  
5 pacing rate from becoming too high can be obtained in a very convenient manner by using a standard pacing lead.

#### Brief Description of the Drawings

The invention will now be described more in detail with  
10 reference to the enclosed drawings on which  
fig. 1a shows the ventricular pressure-volume loop for a heart rate of 60 beats per minute,  
fig. 1b shows the variation of arterial pressure as a function of time for the same heart rate,  
15 fig. 2a and b show the corresponding pressure-volume loop and time variation curve for a twice as high heart rate of 120 beats per minute,  
fig. 3 is a block diagram of an embodiment of the pacemaker according to the invention, and  
20 fig. 4 illustrates the principle of bioimpedance measurement between the tip of an intracardiac electrode and the metal housing of the pacemaker.  
Fig. 5 illustrates the relationships of the cardiac parameters of interest.

#### Description of Preferred Embodiments

As mentioned above, according to one embodiment of the pacemaker according to the invention an upper limit value for the  
30 pacing rate is determined based on a balance between the energy consumption of the myocardium and the energy supplied to the myocardium for high patient workloads.

Since the oxygen demand, or demanded energy consumption which is equal to the work of myocardium, is well correlated to the  
35 area  $S_{dem}$  within the ventricular pressure-volume loop shown in figure 1a, the following equations are valid

$$W = S_{\text{dem}} = \overline{\Delta P} \times SV \quad (4)$$

where  $W$  denotes the work of myocardium,  $\overline{\Delta P}$  the mean value of the ventricular pressure variations during a cardiac cycle, and  $SV$  the stroke volume.

Further, in figures 1 and 2,  $P_{as}$  denotes the atrial systolic pressure,  $P_{ves}$  the ventricular systolic pressure,  $P_{ved}$  the ventricular diastolic pressure and  $P_{ad}$  the atrial diastolic pressure.

The energy supplied to the myocardium can be derived from the time response curve of the arterial pressure shown in figure 1b. The area  $S_{\text{supp}}$  is namely proportional to the supplied energy  $E$ . Thus

$$E = S_{\text{supp}} \times K = (\overline{\Delta P} \times t_{\text{diast}}) \times K \quad (5)$$

where  $t_{\text{diast}}$  denotes the diastolic duration of the patient's heart and  $K$  a coefficient essentially representing the conductance for energy influx into the myocardium. The coefficient  $K$  can be expressed as

$$K = \frac{C_{O_2} \cdot k_{O_2}}{R} \quad (6)$$

where  $C_{O_2}$  denotes the difference of the blood oxygen concentration in the artery and vein, i.e. the oxygen uptake,  $k_{O_2}$  the energy productivity of blood oxygen, and  $R$  the hydraulic resistance of the coronary arteries.

The energy balance  $W = E$  results in

$$\frac{SV}{t_{\text{diast}}} = K \quad (7)$$

Thus, if

$$\frac{SV}{t_{diast}} > K \quad (8)$$

the pacing rate must be reduced, because the myocardium does not get sufficient energy, though the patient's organism, i.e. body, can demand even an increase of the pacing rate.

5

From figures 1 and 2 it appears that the area  $S_{dem}$ , representing energy consumed by the myocardium, increases when the heart rate increases, whereas the area  $S_{SUPP}$  which is proportional to the energy supplied to the myocardium decreases with increasing heart rate. Thus it is obvious that for a certain heart rate energy balance can no longer be maintained.

10

The energy supplied to the myocardium can also be expressed as

15

$$E = V_{mc} \cdot AVD \cdot k_{O_2} \quad (9)$$

where  $V_{mc}$  denotes the blood volume flowing through the myocardium during one cardiac cycle and AVD the arteriovenous blood oxygen difference, i.e. equal to the blood oxygen uptake  $C_{O_2}$ .

20

The blood volume flowing  $V_{mc}$  can be expressed as

$$V_{mc} = \int_0^{t_{diast}} f_c(t) \cdot dt = \bar{f}_c \cdot t_{diast} \quad (10)$$

where  $f_c(t)$  denotes the blood flow per time unit through the myocardium and  $\bar{f}_c$  the mean value of this blood flow.

25

From equations (9) and (10) the following expression is obtained for the supplied energy E.

$$E = \bar{f}_c \cdot AVD \cdot k_{O_2} \cdot t_{diast} \quad (11)$$

30

since

$$\bar{f}_c = \frac{\bar{P}}{R} \quad (12)$$

the supplied energy E can be expressed as

$$E = \frac{\bar{P}}{R} \cdot (AVD \cdot k_{O_2} \cdot t_{diast}) \quad (13)$$

and consequently the coronary resistance as

$$R = \frac{AVD \cdot k_{O_2} \cdot t_{diast}}{SV} \quad (14)$$

in the case of energy balance, i.e.  $E = W$ .

A well known parameter expressing the work ability of the heart is the coronary reserve CR, which can be expressed as

$$CR = \frac{R_{rest}}{R_{min}} \quad (15)$$

where  $R_{rest}$  denotes the resistance of the coronary arteries for the patient in rest conditions and  $R_{min}$  the minimum value of this resistance. Thus the coronary reserve CR expresses directly the ability of coronary arteries to widen during work, the resistance R then being reduced from  $R_{rest}$  to its minimum value  $R_{min}$ . The coronary reserve varies in a healthy heart from about 4 to 6,, but in the case of coronary arteriosclerosis it is lower, typically less than 2.

The current actual value of the ratio  $R_{rest}/R$  is called coronary resistance ratio CRR and equals

$$CRR = \frac{t_{diast,rest} \cdot AVD_{rest} \cdot k_{O_2} \cdot SV}{t_{diast} \cdot AVD \cdot k_{O_2,rest} \cdot SV_{rest}} \quad (16)$$

Since  $k_{O_2,rest} = k_{O_2}$  and by denoting



$$\frac{AVD_{rest}}{AVD} = q \quad (17)$$

q can vary from 1.0 to 0.5, q is decreasing significantly below 1 only in case of anaerobic work of the myocardium. Arteriovenous difference AVD of the oxygen concentration in blood, i.e. oxygen uptake, does not vary significantly with physical load up to the load allowable for the pacemaker patients, i.e. up to anaerobic load limit. This is so due to autonomous regulation of blood circulation inside the myocard.

Thus, the coronary resistance ratio CRR can be expressed as

$$CRR = \frac{t_{diast,rest}}{t_{diast}} \cdot \frac{SV}{SV_{rest}} \cdot q \quad (18)$$

The coronary resistance ratio CRR expresses the degree of utilisation of the coronary reserve CR and when  $CRR = CR$  the complete coronary reserve is utilized, which means that the ability of the heart to maintain the energy balance  $E = W$  has reached near to its safe limit. If the coronary resistance ratio CRR becomes larger than the coronary reserve CR the pacing rate must be limited.

For  $q = 1$  there is no risk for overpacing and for safe limitation of the pacing rate it is suitable to avoid anaerobic operation of the myocardium. Thus the following inequality can be used as criteria for pacing rate limitation.

$$\frac{t_{diast,rest}}{t_{diast}} \cdot \frac{SV}{SV_{rest}} < CR \quad (19)$$

From the equation

$$\frac{t_{diast,rest}}{t_{diast}} \cdot \frac{SV}{SV_{rest}} = CR \quad (20)$$

and the relation

$$T = t_{\text{diast}} + t_{\text{syst}} \quad (21)$$

where T denotes the duration of the cardiac cycle in seconds,  
the following expression is obtained for the upper pacing  
5 rate limit in beats per minute

$$\begin{aligned} \text{upper pacing rate limit} &= 60/T = \\ &= (60 \cdot CR) / [t_{\text{diast, rest}} \cdot (SV/SV_{\text{rest}}) + CR \cdot t_{\text{syst}}] \end{aligned} \quad (22)$$

The parameters stroke volume SV, and the diastolic or  
systolic durations  $t_{\text{diast}}$  or  $t_{\text{syst}}$  are preferably determined  
10 from measured time variations of the electric intracardiac  
bioimpedance, cf. below, and the coronary reserve is obtained  
by standard physical stress test as using veloergometers or  
treadmills.

15 Figure 3 is a block diagram of an embodiment of the pacemaker  
according to the invention comprising a bioimpedance measure-  
ment unit 2 for measuring the time variation of the electric  
intracardiac bioimpedance  $Z_c(t)$ . This type of measurements is  
well known, see e.g. "Design of Cardiac Pacemakers", edited  
20 by John G. Webster, IEEE Press, 1995, pp. 380-386 and US-A-  
5,154,171, 5,280,429, 5,282,840 and 5,807,272. Thus the time  
variation of the intracardiac bioimpedance can be measured  
between the tip 4 of the intracardiac electrode 6 and the  
housing 8 of the pacemaker, when an excitation current is fed  
25 from the electrode tip 4, as schematically illustrated in  
figure 4. Thus a standard pacing lead can be used for this  
measurement.

30 From the measured time variations  $\Delta Z_c(t)$  the parameters for  
calculating the upper pacing rate limit according to equation  
(22) above, or for checking the inequality (19), is determin-  
ed in computing means 10, see figure 3.

The calculated upper limit value is supplied to an upper limit setting means 12 of a pacing rate limiter 14.

A pacing rate controller 16 is also provided for controlling the pacing rate of the pacer or pulse generator 18 in response to the patient's demands. In a limiting unit 20 of the limiter 14 the demanded pacing rate is compared to the set upper limit pacing rate and the actual pacing rate is limited to the set upper limit value if the demanded pacing rate reaches this limit value. Thus in the pacemaker according to the invention an upper limit value for the pacing rate is continuously automatically determined and it is continuously automatically verified that the actual pacing rate does not exceed the present upper limit value. Alternatively, the pacemaker can be modified to continuously monitor that the inequality (19) above is satisfied.

Above bioimpedance measurements are described for determining necessary parameters like stroke volume SV, diastolic or systolic durations  $t_{diast}$  or  $t_{syst}$ . These parameters can, however, also be determined by other techniques. Thus these parameters can be determined from measured ECG's, by ultrasound technique, etc.

The relationships of the cardiac parameters of interest are illustrated in Fig. 5:

If load increases from Rest to some level (e.g. 100W), the stroke volume SV increases 1.2 to 1.5 times, and the diastole time  $t_{diast} = t_{cycle} - t_{syst}$  decreases rapidly with the HR (e.g. 3x).

Falling of the coronary arterial hydraulic resistance due to widening of the blood vessels with the increase of myocardial work  $W = S_{dem}$  compensates the decrease of the myocardial energy supply

$$E = S_{suppl} \cdot K (C_{O_2}; k_{O_2}; R).$$

The compenstion ability can be expressed by the coronary reserve  
CR = 2...5 for a typical patient.

### Claims

1. A rate adaptive pacemaker comprising a means (2) for  
 5 determining the demand of a patient's organism, a pacing rate  
 controlling means (16) for controlling the pacing rate in  
 response to the patient's demand, and a pacing rate limiting  
 means (20) for preventing the pacing rate from becoming too  
 high, **characterized in** that said pacing rate limiting means  
 10 (14) is adapted to limit the pacing rate upwards such that a  
 predetermined relation is maintained between energy supplied  
 to the myocardium and energy consumed by the myocardium.

2. The pacemaker according to claim 1, **characterized in**  
 that said pacing rate limiting means is adapted to limit the  
 15 pacing rate upwards such that the energy consumed by the  
 myocardium always is less than energy supplied to the  
 myocardium.

3. The pacemaker according to claims 1 or 2, **characterized**  
**in** that said pacing rate limiting means is adapted to limit  
 20 the pacing rate such that the inequality

$$(t_{diast,rest}/t_{diast}) \cdot (SV/SV_{rest}) < CR$$

is satisfied, where  $t_{diastrest}$  denotes diastolic duration for  
 the patient in rest conditions,  $t_{diast}$  actual diastolic  
 25 duration for the patient,  $SV$  and  $SV_{rest}$  actual stroke volume  
 and stroke volume for the patient in rest conditions  
 respectively, and  $CR$  the coronary reserve.

4. The pacemaker according to any of the preceding claims,  
**characterized in** that said pacing rate limiting means  
 30 includes an upper limit setting means for setting an upper  
 limit value for the pacing rate, and an upper limit  
 determining means for determining the relation between energy  
 supplied to the myocardium and energy consumed by the  
 myocardium for calculating an upper pacing rate limit value  
 35 from said relation for supply to said upper limit setting  
 means.

5. The pacemaker according to claim 4, **characterized in** that said upper limit determining means includes an energy determining means for determining the energy supplied to the myocardium and the energy consumed by the myocardium respectively, and a comparison means for comparing supplied energy and consumed energy for determining said relation.

6. The pacemaker according to claim 5, **characterized in** that said energy determining means is adapted to determine consumed energy as the product of mean value of ventricular pressure variations during a cardiac cycle and stroke volume.

7. The pacemaker according to claims 5 or 6, **characterized in** that said energy determining means is adapted to determine supplied energy from the time response curve of the arterial pressure during diastole.

8. The pacemaker according to claim 4, **characterized in** that said upper limit determining means is adapted to determine actual coronary resistance ratio (CRR) from the equation

$$\text{supplied energy} = \text{consumed energy}$$

and determine an upper pacing rate limit value from the relation between actual coronary resistance ratio (CRR) and coronary reserve (CR).

9. The pacemaker according to any of the claims 4 - 8, **characterized in** that said upper limit determining means is adapted to determine the upper pacing rate limit value from the equation

$$\text{upper pacing rate limit} = (60 \cdot CR) / [t_{\text{diast, rest}} \cdot (SV / SV_{\text{rest}}) + CR \cdot t_{\text{syst}}]$$

where CR

denotes the coronary reserve,  $t_{\text{diastrest}}$  diastolic duration for the patient in rest conditions, SV and  $SV_{\text{rest}}$  actual stroke volume and stroke volume for the patient in rest conditions respectively, and  $t_{\text{syst}}$  the actual systolic duration.

10. The pacemaker according to any of the claims 3 - 9, **characterized in** that a bioimpedance measurement unit is provided to measure the intracardiac bioimpedance as a

function of time and determine therefrom actual stroke volume SV and actual diastolic or systolic durations  $t_{diast}$  or  $t_{syst}$  respectively.

11. The pacemaker according to any of the claims 3 - 9,  
5 **characterized in** that an ECG measuring and analyzing unit is provided to measure ECG and determine therefrom actual stroke volume SV and actual diastolic or systolic durations  $t_{diast}$  or  $t_{syst}$  respectively.

*Abstract*

A rate adaptive pacemaker comprises means (2) for determining the demand of a patient's organism, a pacing rate controlling means (16) for controlling the pacing rate in response to the patient's demand, and a pacing rate limiting means (20) for preventing the pacing rate from becoming too high. The pacing rate limiting means is adapted to limit the pacing rate upwards such that a predetermined relation is maintained between energy supplied to the myocardium and energy consumed by the myocardium.

Figure 3.



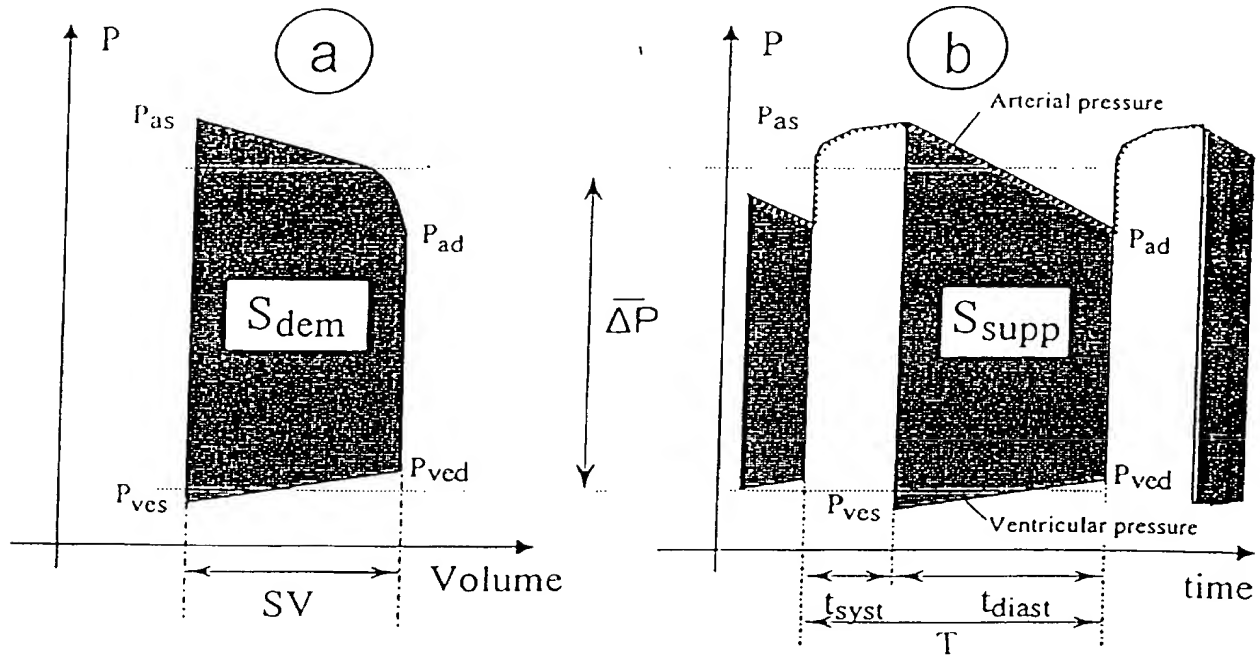


Fig. 1

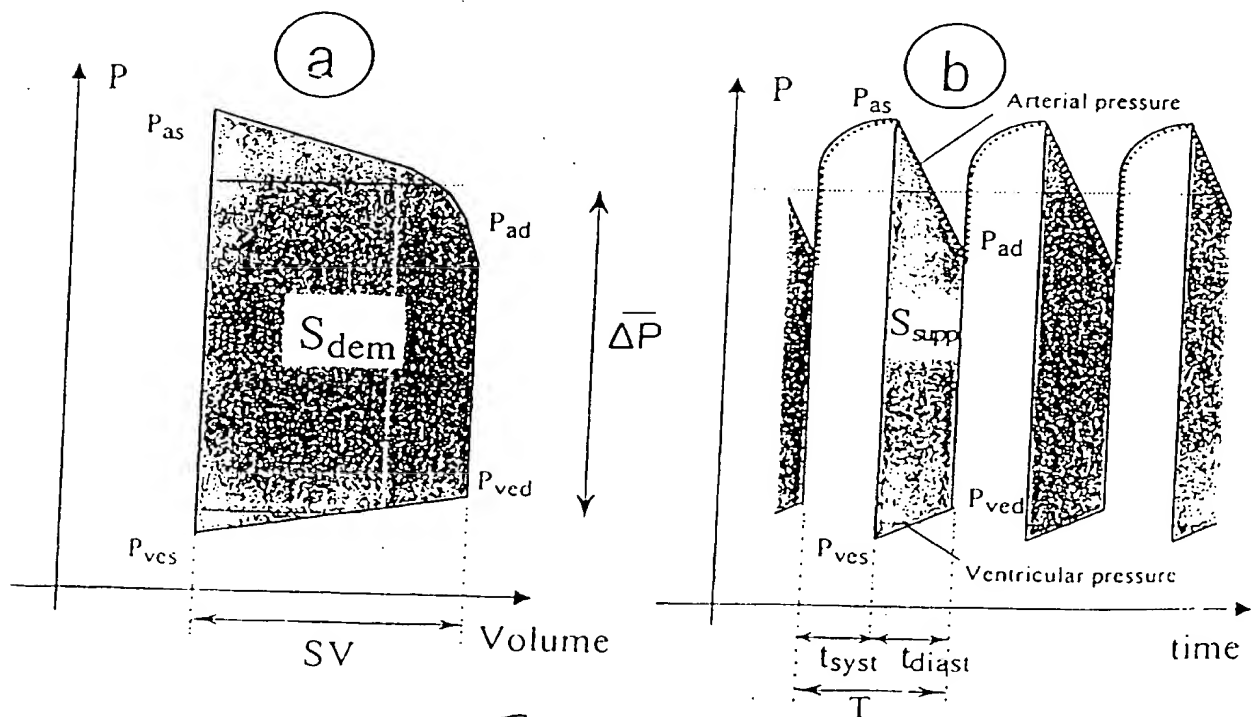


Fig. 2

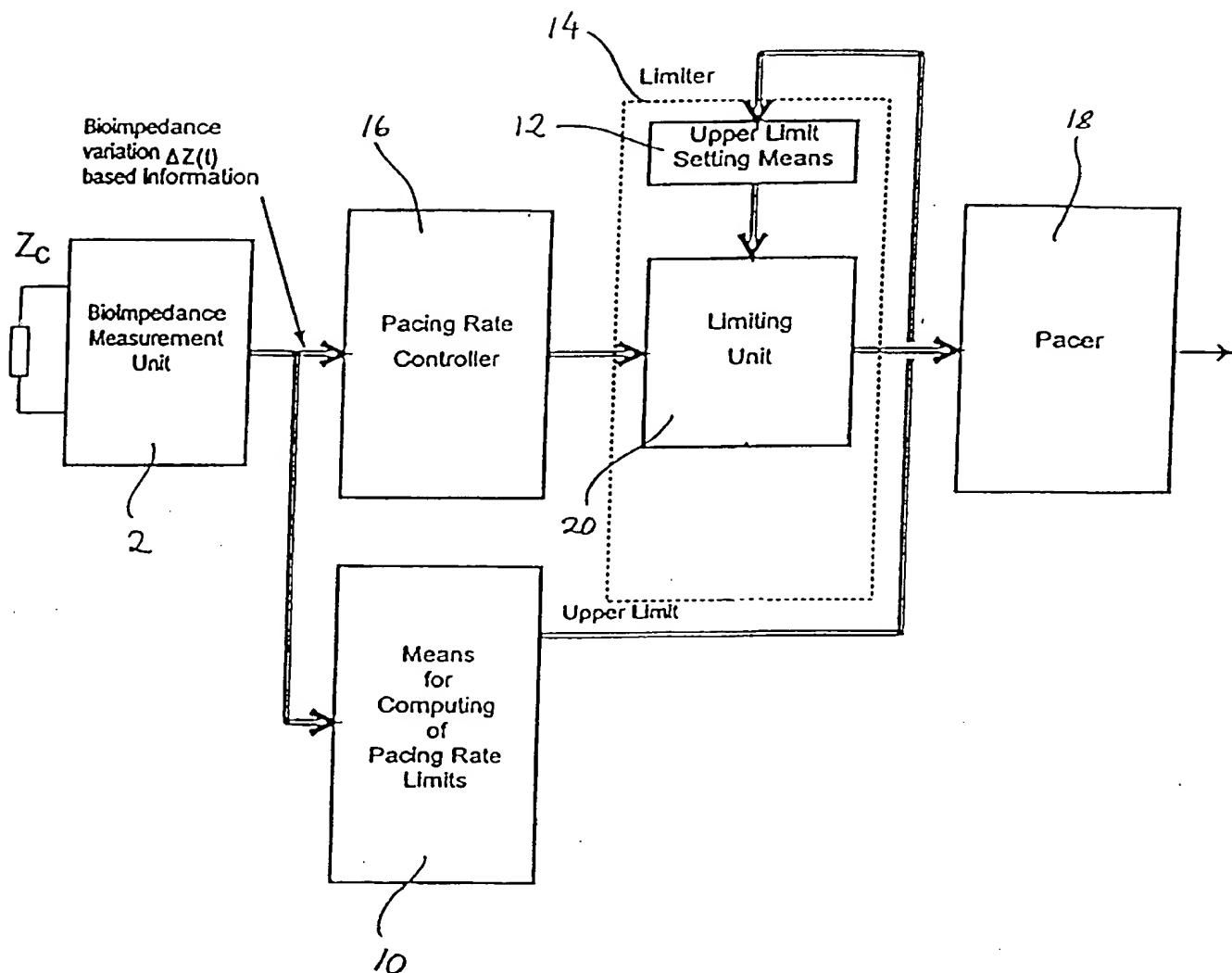


Fig. 3

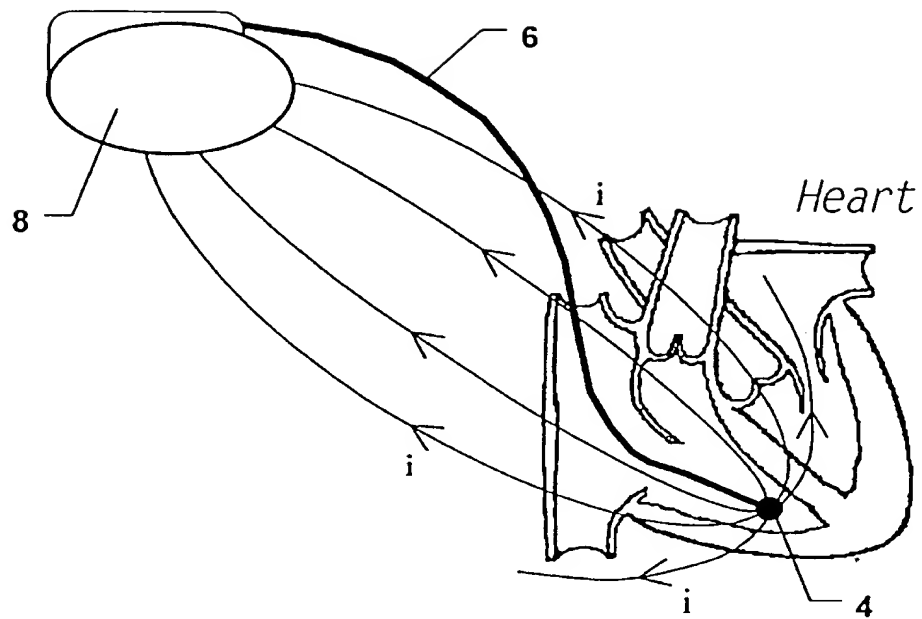


Fig. 4

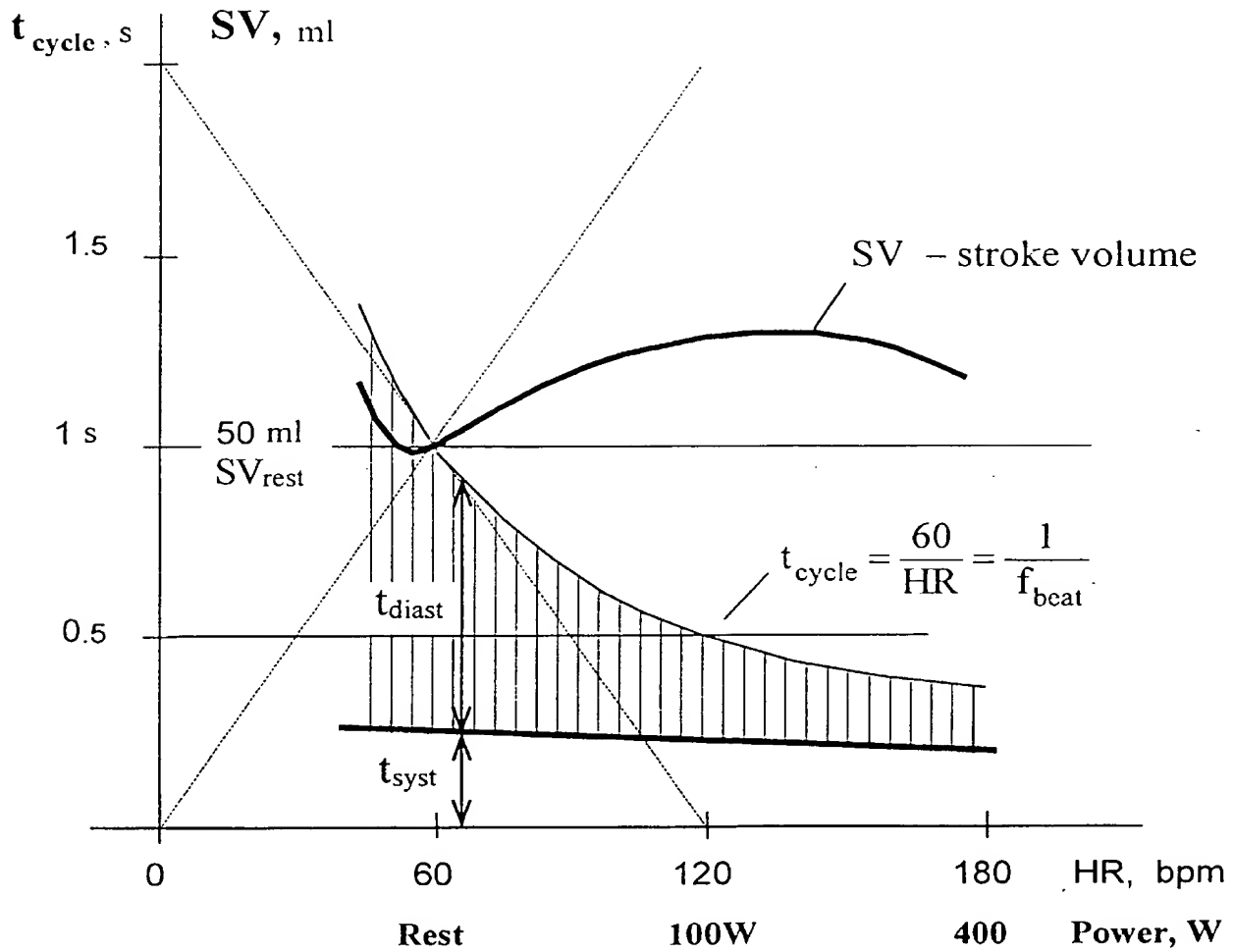


Fig 5